การศึกษาการขยายตัวของรอยร้าวล้าในโลหะเชื่อมยูเทคติกดีบุก-ตะกั่วด้วยกลศาสตร์การแตกร้าวแบบขึ้นกับเวลา

Study of Fatigue Crack Growth of Eutectic Sn-Pb Alloy Using Time-Dependent Fracture Mechanics

ชาวสวน กาญจโนมัย
ภาควิชาวิศวกรรมเครื่องกล คณะวิศวกรรมศาสตร์ มหาวิทยาลัยธรรมศาสตร์
คลองหลวง ปทุมธานี 12120
โทร 02-5643001 ต่อ 3150 โทรสาร 02-5643001 ต่อ 3049 E-mail: kchao@engr.tu.ac.th

Chaosuan Kanchanomai
Department of Mechanical Engineering, Faculty of Engineering, Thammasat University
Klong-Luang, Pathumthani 12120 Thailand
Tel: 02-5643001 Ext. 3150 Fax: 02-5643001 Ext. 3049 E-mail: kchao@engr.tu.ac.th

บทคัดย่อ

โดยทั่วไปวัสดุที่ใช้งานภายใต้ภาระแบบวงรอบที่อุณหภูมิสูง เช่น โลหะเชื่อมในอุปกรณ์อิเล็กทรอนิกส์ มักจะเกิดความเสียหายแบบผสมระหว่างการคืบและการล้า ซึ่งขึ้นกับเวลา ค่าตัวประกอบความเข้มของความเค้น (stress intensity factor, *K*) สามารถใช้อธิบายพฤติกรรมกรรมของรอยร้าวในกรณีการเปลี่ยนแปลงขนาดแบบอิลาสติก ในขณะที่ค่าเจอินทิกรัล (*J* –integral) สามารถใช้อธิบายพฤติกรรมกรรมของรอยร้าวในกรณีการเปลี่ยนแปลงขนาดแบบอิลาสติก-พลาสติก แต่ค่าตัวประ-กอบการแตกหักทั้ง 2 ชนิดนี้ไม่เหมาะสมที่จะอธิบายพฤติกรรมกรรมของรอยร้าวที่ขึ้นอยู่กับเวลา ในงานวิจัยนี้ค่าตัวประกอบการแตกหักแบบขึ้นอยู่กับเวลา (*C**) ได้ถูกคำนวณและใช้อธิบายพฤติกรรมกรรมของรอยร้าวในโลหะเชื่อมยูเทคติกดีบุก-ตะกั่ว (63Sn-37Pb) จากการทดสอบการล้าแบบจำนวนรอบต่ำ (low cycle fatigue) ที่ความถี่ต่างๆ (10^{-3}–10^{-1} เฮิรตซ์) และการทดสอบขยายตัวของรอยร้าวล้า (fatigue crack growth) ที่ระยะเวลาการคงตัวของภาระต่างๆ (5, 20, 30, 50, 100 วินาที) ผลที่ได้จะแสดงให้เห็นว่าค่าตัวประกอบการแตกหักแบบขึ้นอยู่กับเวลา (*C**) สามารถใช้อธิบายอัตราการขยายตัวของรอยร้าวล้าที่ขึ้นอยู่กับเวลาของโลหะเชื่อมยูเทคติกดีบุก-ตะกั่วได้

Abstract

For materials operated under cyclic loading and high homologus temperature condition (T/T_m>0.5), e.g. solders in electronic packages, the materials usually fail under creep-fatigue interaction. Generally, the stress intensity factor (*K*) and *J*-integral can be used to analyze fracture behavior for the case of linear-elastic condition and elasto-plastic condition, respectively. However, the linear-elastic fracture parameter and elasto-plastic fracture parameter may not be the appropriate parameter to correlate time-dependent fatigue crack growth behavior, i.e. creep-fatigue interaction. In the present work, time-dependent fracture parameter (*C**) has been firstly calculated and used to characterize the crack growth behavior of fatigue crack growth (FCG) tests under various hold times (5, 20, 30, 50, 100 seconds), and low cycle fatigue (LCF) tests under various frequencies (10^{-3}–10^{-1} Hz) of Sn-Pb eutectic solder (63Sn-37Pb). The results showed that both FCG and LCF processes of Sn-Pb eutectic solder are dominated by time-dependent mechanism, and *C**-parameter could be successfully used to correlate with the crack growth rates, i.e. the plots of *da/dt* and *C** located in a scatter band with an exponent of 1.

1. Introduction

Recently the assembling technology for electronic packaging has been advanced from plated-through-hole (PTH) to the surface mount technology (SMT). In SMT, the devices are directly soldered to pad on both sides of a printed wiring board. This technology increases the number of mounting devices and decreases the processing cost. However for SMT, the ability for flexing and absorbing the thermal and mechanical strains is reduced. The thermal strains can be arisen due to the mismatch in thermal expansion coefficient between components during processing and service period. Since the solder is softer than other components, most of the cyclic strains and failures are taken place in the solder. The failure is likely to occur especially with the thermally induced low-cycle fatigue. A number of works have focused on isothermal low cycle fatigue (LCF) of solders [1, 2], which is a process of crack initiation and propagation. The LCF life is generally dominated by crack propagation process for LCF of solders [3-6]. However, only a limited number of research works have reported on the fatigue crack growth (FCG) behavior, which is necessary for the life prediction.

For materials operated under high homologus temperature condition (T/T_m>0.5), e.g. solders in electronic packages, the materials usually fail under creep-fatigue interaction [7]. Generally, the stress intensity factor (*K*) and *J*-integral can be used to analyze fracture behavior for the case of linear-elastic condition and elasto-plastic condition, respectively [8]. However, the linear-elastic fracture parameter and elasto-plastic fracture parameter may not be the appropriate parameter to correlate time-dependent crack growth behavior, i.e. creep-fatigue interaction. Logsdon et al. [9] successfully related the fatigue crack growth rate with ΔK for the cyclic-dependent regime of Sn-Pb eutectic solder, however ΔK failed to discuss the effect of time-dependent process. Zhao et al. [10, 11] also found that linear fracture mechanics parameters, such as K_{max}, are not valid in the region of time-dependent crack growth for 63Sn/37Pb and 5Sn/95Pb solders. Kanchanomai et al. [12] studied the FCG behavior of Sn-Ag eutectic solder and found that the ΔJ could not characterize the FCG rate (*da/dN*) for various frequencies, i.e. time-dependent dominant FCG at low frequency and time-independent dominant FCG at high frequency.

On the other hand, the time-dependent fracture parameter (C^*), which is also known as modified *J*-integral, creep *J*-integral or $\dot{J}$, was proposed by Landes and Begley [13], Ohji et al. [14], and Nikbin et al. [15]. As a path independent energy rate line integral, C^* can be used for describing the crack growth rate in the creep-fatigue regime as well as in the creep regime. In the present work, the applicability of C^* to FCG of Sn-Pb eutectic solder (63Sn-37Pb) was disscussed on the basis of the FCG experiments, and the results were compared with those of LCF tests [5].

2. Material and experimental procedures

The material used in the present work was as-cast Sn-Pb eutectic solder (63Sn-37Pb). The detail of microstructure is shown in Fig. 1. The microstructure of 63Sn-37Pb consists of eutectic colonies with lamellae of Pb and β-Sn. By means of linear intercept method, an average colony size is approximately 160 μm. A monotonic tensile test at 20 $^{\circ}$C was conducted up to a strain of 0.03 % under a strain rate of 10^{-2} s^{-1}. The resultant modulus of elasticity, yield stress, tensile strength and elongation were 32 GPa, 18.1 MPa, 39.7 MPa and 38.1%, respectively. The hardness also obtained in this study was 11.8-12.9 HV. The melting temperature of 63Sn-37Pb solder is 183 $^{\circ}$C [16]. From as-cast bar, the round-notched bar (RNB), and round bar (RB) specimens were machined on an NC machine. The geometries of RNB specimen and RB specimen, which were designed according to the ASTM recommendations [17, 18], are shown in Fig. 2.

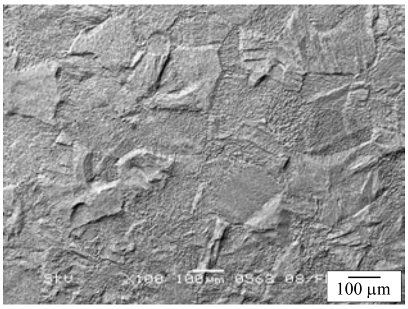

Fig. 1 SEM micrograph of 63Sn-37Pb.

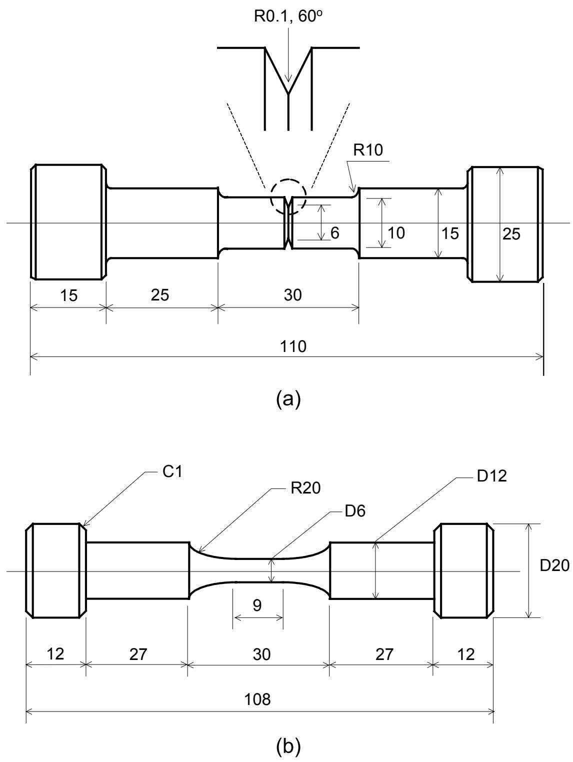

Fig. 2 Geometries of (a) RNB specimen, and (b) RB specimen.

FCG tests were performed with RNB specimens by controlling stress using a servo-hydraulic fatigue machine under 55 % relative humidity, 25 °C temperature (approximately 60% of absolute melting temperature), 0.38 kN maximum load, R = -1 stress ratio, 1 second ramp rate, and various hold time (t_h), i.e. 5, 20, 30, 50, 100 seconds. The waveform of FCG test under 5 seconds hold time is shown Fig. 3. The crack opening displacement (COD or V) was measured at the outside of a notch by using an extensometer with 0.01 μm accuracy.

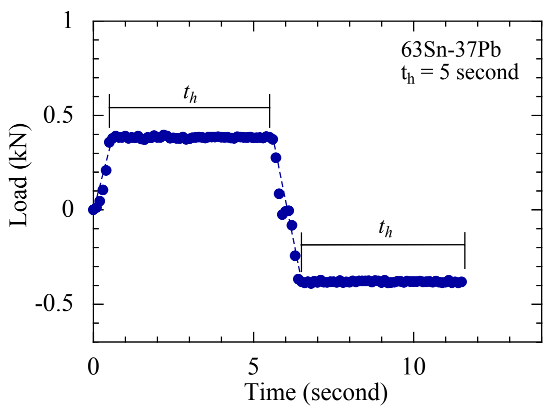

Fig. 3 Relationship between load and time.

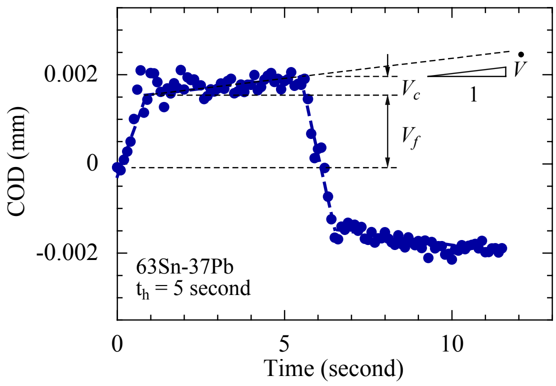

Fig. 4 Relationship between crack opening displacement (COD) and time.

LCF tests were performed with RB specimens by controlling strain using a servo-hydraulic fatigue machine under 55 % relative humidity, 25 °C temperature, 0.5-2% total strain ranges, and R = -1 strain ratio. The triangular waveforms with 10^{-3}-10^{-1} Hz frequencies were used for the LCF tests. The fatigue failure was defined as 25% reduction of maximum tensile load [19]. Details of the LCF experiments were given previously in Ref. [5, 6].

3. Fatigue crack growth rate

The procedure for obtaining FCG rate for RNB specimens tested under various hold times is explained as follows. For the present stress-controlled fatigue tests, the deformation of gage part, measured by an extensometer, can be divided into two stages, i.e. time-independent stage (V_f) and time-dependent stage (V_c), as shown in Fig. 4. The deformation for time-independent stage shows linear-elastic behavior, which can be represented by Hooke's law;

$$\frac{P}{A} = E \cdot \frac{\delta}{L_o} \tag{1}$$

or

$$A = \frac{PL_o}{E\delta} \tag{2}$$

where, P is a maximum load, A is a load bearing area, E is the modulus of elasticity, δ is the deformation, which corresponds to the COD during time-independent stage (V_f), and L_o is the gage length of specimen. Once a macroscopic circumferential crack is formed, it starts to propagate inside the specimen, as shown in Fig. 5. The load bearing area decreases with the propagation of crack and can be represented by the following equation.

$$A = \pi\left(r - a\right)^2 \tag{3}$$

where r is the radius of the cross section of specimen, and a is the crack length. Using Eqs. (2) and (3), crack length at any number of cycles can be calculated from maximum load, COD, material property and specimen geometry. Example of the relationship between crack length and number of cycles is shown in Fig. 6. Consequently, relationships between crack length and time can be obtained, and crack propagation rate (da/dt) can then be calculated. It should be noted that the calculated crack lengths have been compared with those measured directly from the cross-section of failed specimens, and both results were in good agreement.

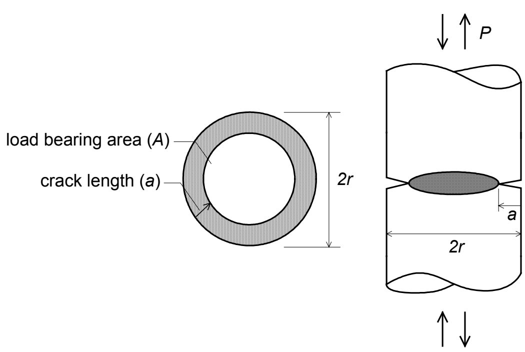

Fig. 5 Schematic of load bearing area and crack length.

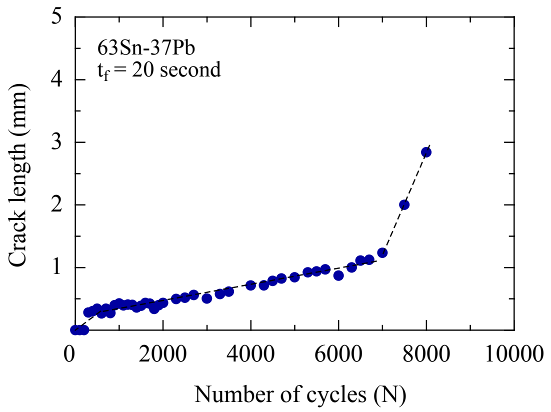

Fig. 6 Relationship between crack length (*a*) and number of cycles (*N*).

For LCF, the indirect method of crack length measurement is also needed for estimating crack length of RB specimen. As the circumferential crack propagates inside the specimen, the load bearing area decreases [20, 21]. Therefore, the load, which is required for maintaining a constant total strain range, decreases with increasing number of cycles. The reduction of load can be divided into three stages; rapid increase stage, steady-state stage and acceleration stage. The steady-state stage dominated the LCF life, and the reduction of load in the steady-state stage approximately reflects the LCF life. From the steady-state stage of the relationship between load reduction and number of cycles, average crack length can be estimated for any number of cycles [4, 6].

4. *C**-parameter

Firstly proposed by Landes and Begley [13], Ohji et al. [14], and Nikbin et al. [15], *C** is a path independent energy rate line integral, which can be used for describing the crack growth rate in the creep-fatigue regime as well as in the creep regime. As a path independent line integral, *C** can be simply modified from the *J*-integral, where strain and displacement are replaced by their rates. Normally, *J*-integral is defined as the potential energy difference between two identically loaded bodies having incrementally different crack lengths.

$$J = -dU/da \quad (4)$$

where *U* is the potential energy. *C** can be calculated in a similar manner using a power rate interpretation, i.e. *C** is the power difference between two identically loaded bodies having incrementally different crack lengths.

$$C^* = -dU^*/da \quad (5)$$

where *U** is the power or energy rate.

Based on the characteristics of applied load and COD obtained, and the *C** estimating method proposed by Ohji et al. [22], *C** for the present RNB specimens were calculated as follows,

$$C^* = \frac{2n-1}{2n+1}\sigma_{net}\dot{V} \quad (6)$$

where, *n* is a creep exponent, which is 6.3 [23], σ_{net} is a net stress, which corresponds to the maximum stress during hold time period, and $\dot{V}$ is the COD rate during the time-dependent stage, as shown in Fig. 4.

Since a *C**-value evaluating equation has not been available for a shallow circumferential crack, *C** for LCF tests could be estimated based on its physical meaning given by Eq. (5). In the present study, *C**-values were calculated in the same manner as Ref. [12].

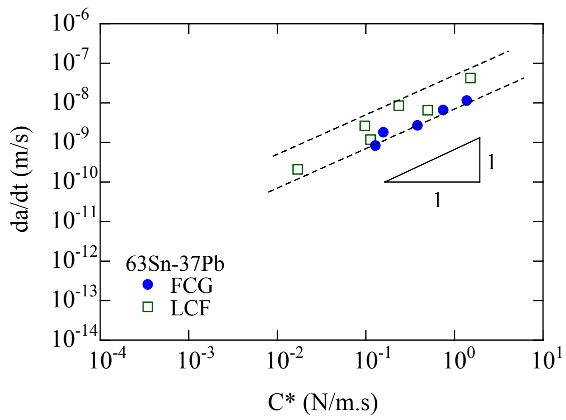

Fig. 7 Relationship between crack growth rate (*da/dt*) and *C**.

5. Results and discussion

Relationships between crack growth rate (*da/dt*) and *C** for FCG test under various hold times are shown together with those of LCF tests under various frequencies in Fig. 7. It is seen that *C** can successfully characterize the crack growth rate of FCG tests, and LCG tests, i.e. all plots are in the scatter band with an exponent of 1. With round notch on the RNB specimen, the FCG tests can be considered as plane strain problem. For LCF tests, a circumferential crack is rather shallow with approximately 400 μm depth, Poisson contraction in the lateral direction can not freely occur around the crack tip and then the state of strain is close to the case of plane strain. Therefore, it is not surprise that the relationship between *C** and *da/dt* of both tests show the similar behavior. Together with the fractographic observations, i.e. evidences of extensive microcracks and voids [4-6, 24], it is confirmed that the FCG, and LCF processes are dominated by time-dependent mechanism, their crack growth rates (*da/dt*) can be characterized by time-dependent fracture parameter (C^*).

6. Conclusion

Crack growth behavior of Sn-Pb eutectic solder (63Sn-37Pb) for FCG tests under various hold times (5, 20, 30, 50, 100 seconds), and LCF tests under various frequencies (10^{-3}–10^{-1} Hz) has been studied using RNB, and RB specimens, respectively. Time-dependent fracture parameter (C^*) has been firstly calculated and used to characterize the crack growth rates. The results showed that C^*-parameter successfully correlated with the crack growth rates of FCG, and LCF tests, i.e. the plots of *da/dt* and C^* located in a scatter band with an exponent of 1.

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